DETERMINATION OF SAFE PULLING LOADS ON FUSIBLE PVC PIPE DURING HORIZONTAL DIRECTIONAL DRILLING INSTALLATIONS

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ABSTRACT: Urban population growth has resulted in the need to install new underground municipal distribution systems to meet increased demand. To address this pressing issue, municipal engineers are attempting to better understand the pipe material and construction options available for their public works utility projects. Currently, there are numerous alternative pipe products to choose from for installations using trenchless construction methods such as Horizontal Directional Drilling (HDD). HDD enables installations of buried infrastructure with minimal disruption to surface activities. The nature of the HDD process necessitates the use of continuously joined pipe products capable of being pulled in, as opposed to pushed segmental installations. Subsequently, Fusible PVC™ pipe has proven to be a feasible option for potable water, force main, reclaimed water, and gravity projects employing directional drilling. While maximum Safe Pull Forces have been developed for Fusible PVC™, the present Pull Force predictive tools seem to be overly conservative in evaluating Safe Pull Force for a specific installation. To this end, this paper provides an overview of a three step process used to define the methodology of predicting Safe Pull Forces on Fusible PVC™. Step #1 is the development of empirical equations based on existing methodologies, experience, and PVC properties. Step # 2 is the actual field measurement of Safe Pull Forces on the Fusible PVC™ during HDD pull back. The third step is to compare the actual data to the calculated data and adjust the predictive equations accordingly. In-line measuring devices like the TensiTrak™, attached between the backreamer and the product pipe, were used to measure actual pull loads on the pipe during numerous field installations for comparison with predicted design loads. A practical approach for evaluation of Safe Pull Force determination methodology is presented in this paper that includes basic engineering principles in Safe Pull Force evaluation and how these are applied to Fusible PVC™.

1.   INTRODUCTION

The use of trenchless construction methods for the installation of wastewater and potable water distribution systems have increased over the past decade. The most recent 2005 Infrastructure Report Card from the American Society of Civil Engineers (ASCE) gave the nation's wastewater and drinking water systems both failing grades of D- (ASCE, 2005). Surprisingly, this is similar to the grade given in the past two report cards. Subsequently, the need to replace these aging systems is now even more pressing in the interest of public health. Combine that with an increase in urban population growth resulting in the need to install new municipal distribution systems, and now consideration of this segment of the underground utility market is even more important.

To address these aging systems, municipal engineers are trying to better understand the pipe material options available for their public works utility projects. Currently, there are numerous alternative pipe products to choose from for installations using trenchless methods such as Horizontal Directional Drilling (HDD). HDD enables installations of utility lines with minimal disruption to surface activities. Subsequently, this technique has had an explosive growth over the past decade. The nature of the HDD process necessitates the use of continuously joined pipe products capable of being pulled in, as opposed to segmental installations. Fusible PVC[TM] pipe has proven to be a feasible alternative to other options including: high density polyethylene (HDPE); ductile iron; and gasketed or jointed PVC. Favorable material properties inherent to PVC include: 1) durability; 2) corrosion resistance; 3) resistance to chemicals; 4) high tensile strength and HDB; and 5) cost-competitiveness. However, development of analytical procedures to determine design characteristics of this product is imperative to broadening its use. An analytical procedure for determining safe pulling forces and an associated Factor of Safety would aid engineers and contractors in selecting Fusible PVC™ for Horizontal Directional Drilling projects as a viable and economical option. A scholarly approach to evaluation of design methodology is important to ensure that basic engineering principles are met during installation and to satisfy the requirements of municipal agencies.

Established equations for calculating pull loads during HDD installations were developed in ASTM F1962-05 "Standard Guide for the Use of Maxi-Horizontal Directional Drilling for Placement of Polyethylene Pipe or Conduit under Obstacles, Including Rivers" (ASTM, 2005). The equations developed in ASTM F1962-05 were used as a basis and modified for calculating pull loads using Fusible PVC[TM] pipe. The calculations were compared to actual pipe loads captured during field installations of Fusible PVC[TM] pipe using in-line measuring devices. This paper presents results of safe pulling loads from two projects completed in 2007. It should be noted that research is on-going to compare pull load values taken from a number of HDD projects.

2. STANDARD EQUATIONS

Published equations from ASTM F1962-05 were the basis used to calculate predicted pull loads of HDD installations using Fusible PVC™. Material property variations of PVC from HDPE pipe are captured in the calculations presented in this paper. Figure 1 illustrates the basic geometry of Horizontal Directional Drilling (HDD) installations along a borepath (modified from ASTM F1962-05, 2005).
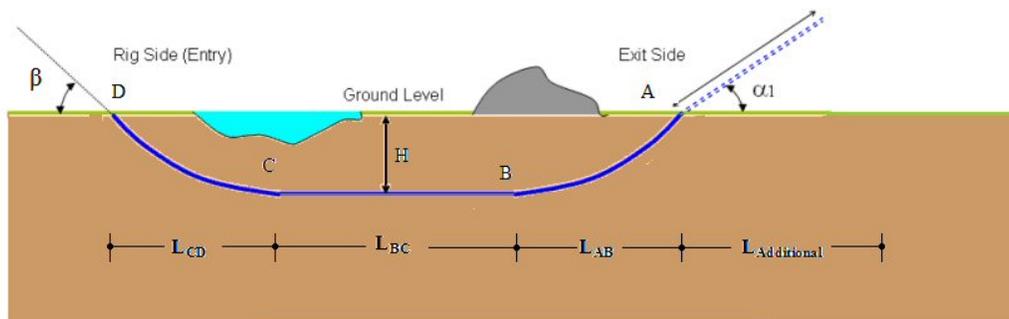

Figure 1. General Borepath Schematic of a Typical HDD Installation

As illustrated in Figure 1, there are four critical points along a given borepath that pull loads are calculated to determine the maximum pull load encountered during an HDD installation. Varying degrees of frictional forces may be found on the pipe outside of the borehole. It is suggested that rollers be used to prevent opposite (negative) pulling forces acting counter to the direction of installation (Bennett et al. 2005). This also reduces potential damage to pipe being dragged along a rough surface. Rollers used in the Secession Reclaimed Water Force Main project in South Carolina are shown in Figure 2.

Figure 2. Fusible PVC™ Pipe on Rollers

3. FIELD PROJECTS USING FUSIBLE PVC PIPE

3.1 Secession Reclaimed Water Force Main Project in South Carolina

3.1.1 Project Background

The Beaufort Jasper Water and Sewer Authority (BJWSA) is a non-profit, non-taxing public service organization that provides water and sewer service to an area of approximately 750 square miles including two counties in South Carolina. The BJSWA Port Royal Wastewater Reclamation Facility produces a reclaimed water quality effluent which allows it to be used for mostly unrestricted irrigation purposes.

The Secession Golf Course was to be tied into the Port Royal WRF effluent force main on Port Royal Island near McTeer Bridge, which traverses the Beaufort River from Port Royal Island to Lady's Island. Once back on to Lady's Island, traditional construction methods would suffice in getting the effluent reuse water to the Secession Golf Course and eventually other end users of the water. Horizontal Directional Drilling (HDD) was considered early on in the design process as a possibility to install the pipe under the river. The engineering firm of Hussey, Gay, Bell, and DeYoung was hired by BJWSA to design the Secession Reclaimed Water Force Main project and a 10" nominal diameter DR 14 Fusible PVC™ pipe was chosen as the pipe material to complete the crossing.

The contractor, Mears Group, mobilized a 330,000 pound drill rig on Friday, May 18th, 2007 with initial set up on the east side of the alignment on Lady's Island on Saturday, May 19th. The initial pilot bore was accomplished using a mud motor and a 12 1/4" bit. Drilling commenced on Tuesday, May 22nd, and was complete on June 1st. The drill stem reached the west side of the alignment around May 29th. A 36" outfall was found to be about 5' south of the assumed plan position. Subsequently, the drill stem was pulled back approximately 600 feet and re-drilled by steering to the south. This allowed the drill stem to come up along side the 36" outfall.

The initial bore path was back reamed in a single pass with a 17.5" diameter back reamer. Reaming was started on June 2nd and was complete on June 7th. During this process, Mears utilized a second 60,000 pound drill rig, located on the west side of the river. The function of the second rig was to exert tension on the drill pipe string while the primary 330,000 pound rig provided rotation. The alignment was then swabbed by pulling the reamer back through a second time to ensure debris was completely removed from the alignment.

Due to layout constraints, shorter sections of pipe were pre-fused, with final assembly taking place during the pipe installation. Five pipe lengths were created with each length around 1,000 ft long. Fusion started on May 22nd and was completed on June 6th. This left four intermediate fusions to be performed during the pullback. The total length of pipe installed was 5,120 LF.

Pipe pullback started on Monday, June 11th, 2007. Preparations were made and pipe connected to the drill string between 6 AM and 9 AM with actual pipe pullback starting at approximately 9 AM. Rollers were used to minimize frictional forces acting on the pipe while outside of the borehole. The main pull-in with pipe exiting the alignment on the east side took approx 17¼ hours. Removal of reamer and final positioning took an additional 1¼ hours for a total of 18½ hours.

3.1.2 In-Line Pull Force Monitoring Device

Pull force was monitored in two ways for this installation. First, for each drill rod segment, the hydraulic pressure and gear used at the drill rig were recorded. This captured the pull force based on the machine hydraulics that was required to move the drill stem, back reamer, drill mud, spoils, as well as the pipe. The approximate conversion factor from gauge pressure to pull force was coordinated and verified with Mears. The second measurement was taken from an in-line pull force monitoring device rented from Horizontal Technologies of Houston, TX (Figure 3). This device was developed to record downhole information as it relates to the pipe and the borehole. The device was connected between the swivel and the back reamer with a standard threaded connection that matched up to the drill stem, reamer, and swivel threaded connections. Because of the back reamer and mud flow required, the device could not be hard wired to the surface for real time data gathering and because the river crossing was under brackish water, transmission signals from a monitoring device could not be readily received. All data was recorded for the entire length and duration of the pull, even through it lasted over 18 hours. The device measured tensile force, external mud pressure, drilling fluid pressure in the drill stem, and torsion forces translated to the pipe. Data points were recorded every 10 seconds and stored on board the device. After the pullback was complete, the device was returned for data retrieval. This data allowed for comparison of pull force at the pipe to the pull force at the machine moving the drill stem, back reamer, and the pipe.

Figure 3. In-line Pull Force Measuring Device

3.1.3 Pulling Load Calculations

The project involved the installation of 5,120 ft. of 10" nominal diameter DR 14 Fusible PVC™ pipe. The maximum bore depth was 60 ft. in clayey soil conditions. The horizontal lengths were: $L_2 = L_{AB}$ = 600 feet; $L_3 = L_{BC}$ = 3900 feet; and $L_4 = L_{CD}$ = 600 feet. Unique aspects of this project involved the decision to pre-

fuse five 1,000 (+/-) foot sections of pipe and perform intermediate fusion joints during installation as opposed to pre-fusing the entire pipe length and pulling it all in continuously. Subsequently, the design calculations were modified to reflect the pulling of multiple fused sections as outlined in the following pages.

Firstly, Hydrokinetic Force (T_{HK}) should be calculated from [1] as:

$$T_{HK} = \frac{q * \pi (1.5O.D^2 - O.D^2)}{8} = 605 \; psi \tag{1}$$

Where;
q = hydrokinetic pressure = 10 psi

Modifications of the basic pull load equations (eq. 8 to 11) from ASTM F1962-05 are found in [2], [3], [5], and [6] on the following pages:

Load at Point A (Figure 4):
$$T_A = v_a \cdot w_a \cdot L_{1000} \tag{2}$$

Where;
v_a = Coefficient of friction applicable at the surface before the pipe enters the bore hole (i.e. 0.1)
w_a = Weight of empty pipe per foot
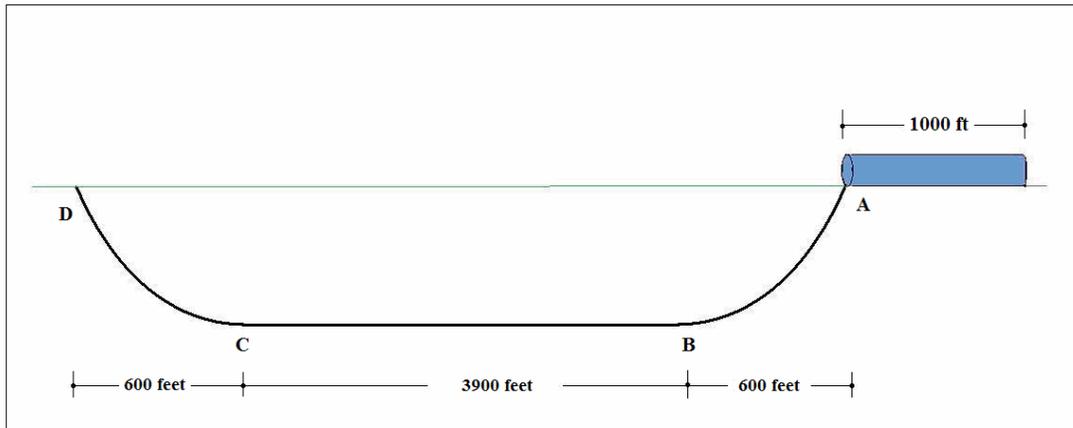$L_{1000 \; feet}$ = Length of pipe (1,000 feet)

Figure 4. Pipe at Point A along the Alignment

Load at Point B (Figure 5):
$$T_B = T_A + [\exp(v_b * \alpha)v_b * w_b * L_{600}] + (v_a * w_a * L_{1400}) + (w_b * H) \tag{3}$$

Where;
v_b = Coefficient of friction between pipe and slurry
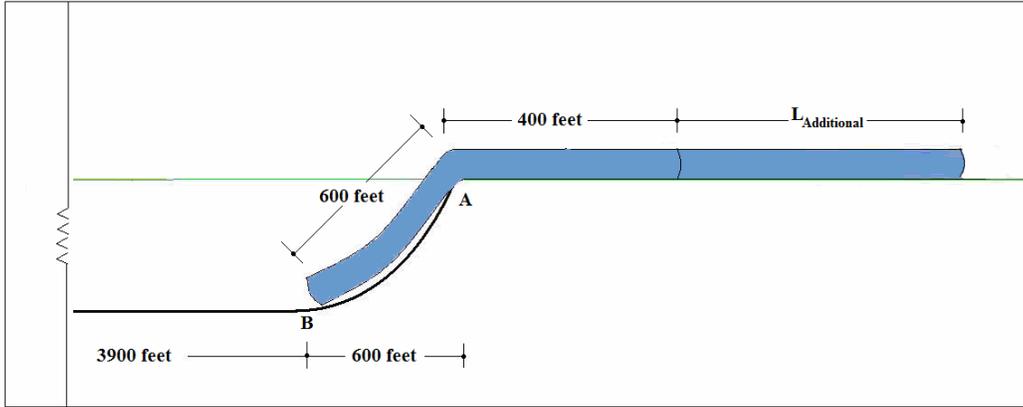w_b = Buoyant force (when pipe is filled with water)
H = Installation depth (60 ft)

Figure 5. Pipe at Point B along the Alignment

A vertical Capstan effect exists between Point A to B as follows:

Capstan Effect = $\exp(v_b * \alpha)v_b * w_b * L_{600 \text{ feet}}$ = [exp (0.3*0.2)*0.3*15.12*600] = *2,890 lbs*   [4]

Where;

θ = Entry (α) and exit (β) angles of bend in pipe

Load at Point C (Figure 6):
$T_C = T_B + (v_b * w_b * L_{3900 \text{ feet}}) + (v_a * w_b * L_{100 \text{ feet}})$ + (Horizontal Capstan effect at C)   [5]
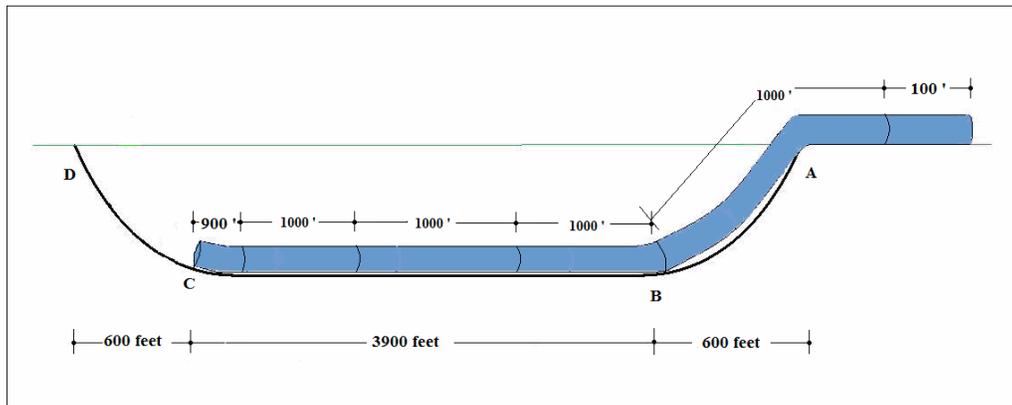

Figure 6. Pipe at Point C along the Alignment

A horizontal curve of 30 degrees (0.5253 radians) created a horizontal Capstan effect at points 1000 feet through 1800 feet as follows, which must be included in the pull force calculation at Point C along the borepath using [4]:

Capstan Effect (Horizontal) = exp (0.3*0.5253) 0.3* 15.12* 800) = *4,248 lbs*   [4]

Load at Point D (Figure 7):
$T_D = T_C + [\exp(v_b * \beta)v_b * w_b * L_{500}]$ + (Horizontal capstan effect at D) – $(w_b * H)$ [5]
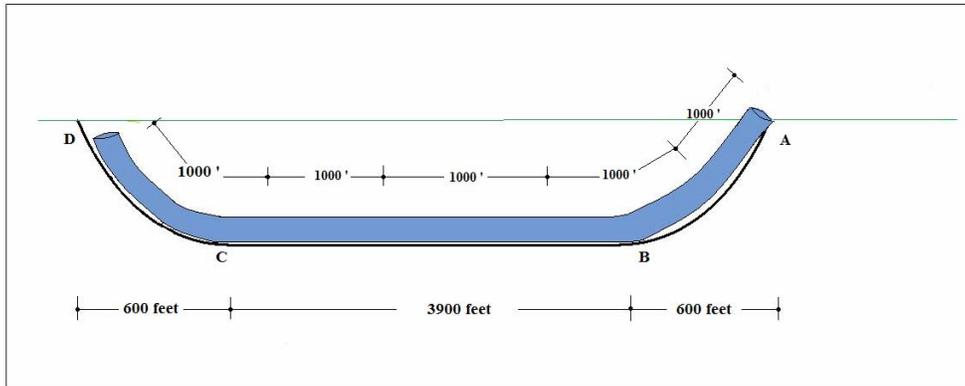
Figure 7. Pipe at Point D along the Alignment

A second horizontal curve of 25 degrees (0.44 radians) created a horizontal Capstan effect at points 3,900 feet through 4,100 feet as follows, which must be included in the pull force calculation at Point D along the borepath using [4]:

Capstan Effect (Horizontal) = exp (0.3*0.44) 0.3* 15.12* 200) = *1,035 lbs*   [4]

Summarizing the pull force calculations:

From Equation [2],

T_A = (0.1 * 16.97 * 1000) = *1,697 lbs*

From Equation [3],

T_B = 1697 + [exp (0.3 * 0.2) 0.3 * 15.12 * 600] + (0.1 * 16.97 * 1400) + (15.12 * 60) = *7,870 lbs*

From Equation [5],

T_C = 7870 + (0.3 * 15.12 * 3900) + (0.1 * 16.97 * 100) + [exp (0.3 * .5253) 0.3 * 15.12 * 800] = *29,978 lbs*

From Equation [6],

T_D = 29,978 + [(exp (0.3 * 0.2) 0.3 * 15.12 * 500] + (exp (0.3*0.44) *0.3 *15.12 * 200) - (15.12 * 60)
   = *32,514 lbs*

The Total Maximum Pull Force (Predicted) is the Maximum Force (T_D) + Hydrokinetic Force (T_{HK}):

Total Maximum Pull Force (Predicted) = 32,514 lbs+ 605 psi = *33,119 lbs*

Total Maximum Pull Force (Actual) = *34,491 lbs*

Figure 8 illustrates the predicted and actual pulling forces at each of the four points along the borepath. The predicted lines show the transition from the initial trial equations to the current approach when pulling longer sections of pre-fused pipe sections fused together during installation. The actual forces were captured from the in-line monitoring device. The results for the Secession Reclaimed Water Main project show a good correlation between the predicted and actual captured pulling forces. This is an attempt to develop some basic design criteria for Fusible PVC™ pipe installed by HDD. It is anticipated that more and more projects will use pre-fused sections and then do intermediate field fusion during installation. Subsequently, the equations used better reflect actual conditions than the traditional equations found in

ASTM F1962-05, which assume that the entire length of pipe will be first fused and then pulled in continuously. It is worth noting that observations of the hydraulic force measurements at the drill rig indicated a maximum force reading of approximately 66,000 pounds, which is almost twice the force measured at the pipe.
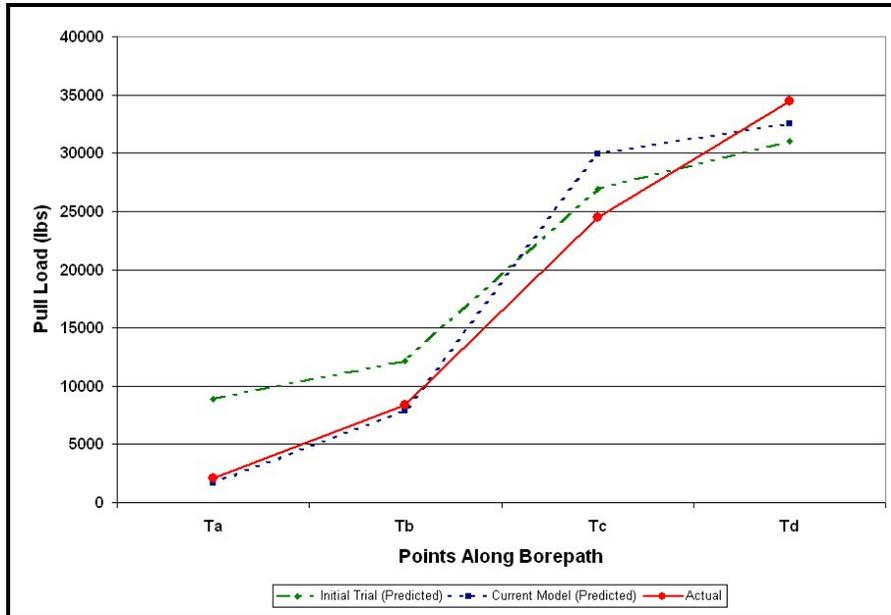

Figure 8. Predicted vs. Actual Pull Loads for the Secession HDD Project

3.2   City and County of Broomfield, Colorado Industrial Lane HDD Project

3.2.1   Project Background
The City and County of Broomfield, a municipality located between Denver and Boulder, needed to upsize and replace an existing waterline under a busy service road in an area of small industrial and commercial businesses for fire flow and other service reasons. Industrial Road, though only a two lane thoroughfare, sees substantial traffic flow, so Broomfield decided to install a new line using HDD technology and Fusible PVC™ as the product pipe. One end of the new line connected to an existing 24" ductile iron pipeline, via a tee, while the other end of the line reduced back into the existing 12" ductile iron pipeline, once past the commercial zone.

The work was completed in one HDD installation of approximately 1,000 feet in late July 2007. Twenty-six pipe lengths of 16" DIPS DR 18 (Fusible C-905®), 40 feet long were delivered and fused, using a total of 25 joints, to create one product string. Pullback was performed in one day, on August 17th, 2007, starting at approximately 9 AM, and lasting until 3 PM with final connections made a week later. No ballasting was performed on the pipeline during installation.

Drilling operations were performed from July 30th, 2007 to August 16th. The drilling contractor, BTrenchless, a division of BT Construction, Henderson, CO, used a Ditch Witch JT4020 to perform the drilling and pullback. The rig was setup on a shoulder along Industrial Lane. The drill was inserted on an angle, both into the ground and towards the center of the road. This was then corrected to come into line with the roadway and at the appropriate depth of around 8 feet. The bore passed under an existing 24" ductile iron (DIP) water main that the pipe would later tie into. The bore continued straight along the roadway (along the left edge of the road surface) as it progressed. At a point approximately 400 feet from the 24" DIP water line crossing, the drill path began to drop in elevation. This culminated, 300 feet (approximately) later at 12 feet of depth, where it crossed under an exiting culvert. From this point, over the next 300 feet, the drill curved back to the road surface and terminated at the pipe insertion pit. This termination has a slight bend to the left so that the pipe was inserted on the side of the road and not

through the pavement. The alignment was back-reamed and swabbed one time with the final 22" diameter reamer prior to the installation of the pipe, to clean the borehole of any remaining debris.

3.2.2 In-Line Pull Force Monitoring Device
An in-line pull force monitoring device developed by Digital Control Inc. was used to capture pull load data on the pipe during installation. The TensiTrak™ tension load and drilling fluid pressure monitoring device includes a strain gauge and a pressure-measuring device, which are connected to a transmitter. The transmitter transmits load and pressure readings in real time on the frequency used by the Eclipse® locating system. The information transmitted includes the instantaneous pull force, maximum pull force, drilling fluid pressure, transmitter temperature, transmitter battery life and a magnetic signal, which can be used to locate the depth and direction of the TensiTrak monitor should this be desired. The instantaneous pull loads and drilling fluid pressures are also transmitted in real time by the Eclipse receiver to the Eclipse remote at the drill rig.

The TensiTrak monitor is connected to a swivel between the reamer and the product pipe being installed to ensure that only the load on the product pipe itself is measured as shown in Figure 9. This is important since traditionally there is no way to gauge whether increased pulling loads are caused by reamer loads, (i.e. in harder ground conditions), loads of the product pipe or a combination of both. In case of increased loads evidenced by hydraulic pressures on the drilling machine, the TensiTrak readout identifies where the issue might lie.

The TensiTrak monitor is available in two versions, a 60,000 and 100,000 pound load reading capability. The mechanical capability of the units, however, far exceeds those levels. Load data is displayed in 15 lb. increments. The drilling fluid pressure is displayed in 1 psi increments and the system is capable of measuring pressures as high as 127 psi. Although data is sampled much more often, readings of fluid pressure and tension are displayed every four seconds on the receiver display. The tension monitor is powered by three C-cell alkaline batteries providing 15 hours of continuous operations with a transmitting range of approximately 60 ft.

Figure 9. TensiTrak™ In-line Pull Force Measuring Device

3.2.3 Pulling Load Calculations
Predicted pull loads were calculated using equations derived from ASTM F1962-05. In this project, the product pipe was installed traditionally (continuously) with all sections fused together (as opposed to the Secession project where in-field fusion of large sections were performed).

<u>Load at Point A:</u>
T_A = exp ($v_a\alpha$) ($v_a w_a$ ($L_1 + L_2 + L_3 + L_4$))
   = exp (0.1 * 0.2) (0.1 * 120.56 (0+ 100 + 800 + 100)) = *3,469 lbs*

<u>Load at Point B :</u>
T_B = exp ($v_b\alpha$) ($T_A + v_b|w_{b1}|L_2 + w_{b1}$ H - $v_a w_a L_2$ exp ($v_a\alpha$))
   = exp (0.3 * 0.2) (3469 + 0.3 *120.56 * 100 + 120.56 * 10 – 0.1 *34 * 100 * exp (0.1*0.2)) = *8,420 lbs*

<u>Load at Point C:</u>
T_C = $T_B + v_b|w_{b1}|L_3$ – exp ($v_b\alpha$) ($v_a w_a L_3$ exp ($v_a\alpha$))
   = 8420 + 0.3 * 120.56 * 800 – exp(0.3 *0.2) (0.1* 120.56* 800 exp(0.1*0.2)) = *26,906 lbs*

Total Maximum Pull Force (Predicted) = 26,906 + 1,486 = <u>*28,394 lbs*</u>

Total Maximum Pull Force (Actual) = <u>*22,710 lbs*</u>

4.   CONCLUSIONS AND RECOMMENDATIONS

As contractors and engineers look to evaluate pipe material options for projects involving Horizontal Directional Drilling, they should consider the viability of Fusible PVC™. This paper presented a methodology for calculating predicted pipe pull loads using equations based on ASTM F1962-05. The predicted values were compared to actual loads captured from in-line pull force monitoring devices used on two field projects. The equations presented in ASTM F1962-05 are based on pulling the entire pipe product string in a single pullback. Further modification of these basic pull load equations for plastic pipe were done to capture projects where longer sections of pre-fused pipe sections are pulled and fused together during installation. Typically, this would be performed on longer distance installations where space constraints may dictate.

A comparison of results from the 5,120 ft Secession Reclaimed Water Force Main installation of 10" nominal diameter DR 14 FPVC™ revealed a 4% difference between maximum predicted (33,119 lbs) and actual (34,491 lbs) pull loads. This shows an excellent correlation from the field to suggested design methodology for this case. There was a 20% difference between the maximum predicted (28,394 lbs) and actual (22,710 lbs) pull loads from the Broomfield, Colorado Industrial Lane installation.   The difference reveals a 1.25 Factor of Safety between predicted and actual, with the predicted results being conservative.

Admittedly, only two field projects have been used for comparison; however, the results presented in this paper demonstrate the need for designers and contractors to capture field data using in-line pull force monitoring devices to better calibrate their predictive models. Continued research is underway to capture field results from in-line monitoring devices installed in 4 to 6 more Horizontal Directional Drilling projects using Fusible PVC™. This would further improve the accuracy of predictive models for determining maximum safe pulling loads.

5.   REFERENCES

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